FIRST SOLAR'S CdTe MODULE MANUFACTURING EXPERIENCE; ENVIRONMENTAL, HEALTH AND SAFETY RESULTS

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ABSTRACT

Consistent with First Solar's proactive cadmium-containing material management practices such as CdTe PV module recycling, this paper reviews our activities and results in preventing environmental exposures and human health risks associated with cadmium materials processing during module manufacturing. Industrial hygiene data for manufacturing activities are presented and engineering controls are discussed. Medical monitoring results comparing recently hired to long-term employees and smokers is reported. Environmental releases to air, water and land have been quantified. The First Solar safety management system is outlined.

INTRODUCTION

For nearly the last decade, originally as Solar Cells, Inc. and now as First Solar, LLC, we have been engaged in pilot scale production (less than 500 kW annually) of cadmium telluride photovoltaic modules. The toxicological and environmental exposure effects of cadmium and cadmium compounds are well known[1]. During this period, much data has been accumulated on all facets of worker and environmental exposures to the cadmium compounds we use to manufacture this product. For instance, over 700 medical monitoring tests for blood cadmium, urine cadmium and β_2-microglobulin excretion have been done on First Solar workers to track any biological responses to occupational cadmium exposures. Hundreds of industrial hygiene air samples have been collected to determine cadmium exposure during specific manufacturing processes and maintenance procedures. Further, air emissions, emissions as industrial wastewater and solid wastes have been either measured or calculated using engineering estimates such as mass balance. The cadmium management effort is complimented by a comprehensive safety management system. The heart of this system is a formal hazard recognition system designed to identify and proactively control workplace hazards. The objective of this paper is to show that advanced hazardous materials and safety management techniques, supported by employee medical monitoring and process emissions testing, can prevent environmental exposures and human health risks from cadmium based on our pilot scale manufacturing experience.

METHODOLOGY

Employee medical monitoring data was collected using the assistance of Dr. Eric Schaub MD at the Medical College of Ohio's Occupational Medicine Services, Toledo, Ohio. The Medical College uses Pacific Toxicology Laboratories, Los Angeles, CA for cadmium analysis in blood and urine once specimens have been collected.

Industrial hygiene air sampling data was collected using an SKC *Aircheck* model 224-52 air sampling pump equipped with an 0.8μ methylcellulose-ester (MCE) collection filter cartridge in accordance with accepted standard sampling practices such as flow calibration before and after sampling. Brighton Analytical Labs, Brighton, Michigan, did the cadmium analyses using atomic absorption flame spectroscopy.

Environmental release data were collected by directly measuring using appropriate sampling and analytical procedures and indirectly by engineering (mass balance) calculations.

MEDICAL MONITORING RESULTS

The following three figures are charts comparing average cadmium medical monitoring results at time of hire (baseline) to their most current medical monitoring data. The 22 individuals in this population subset were chosen for analysis based on their proximity to cadmium processes and maintenance activities. These are the First Solar employees who have worked most closely and for the longest time (varying from at least 3 and up to 7 years) in the semiconductor processing areas of the pilot manufacturing plant.

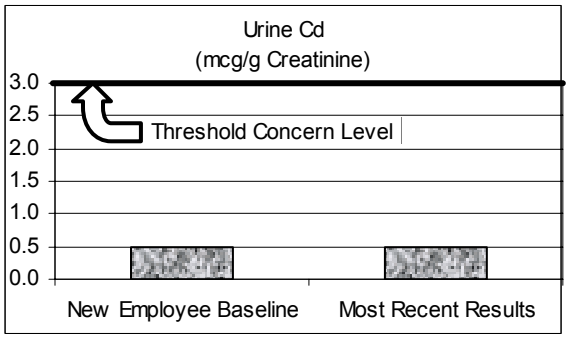

Fig 1. Baseline Vs current employee urine cadmium levels (normalized to μg Cd/g creatinine).

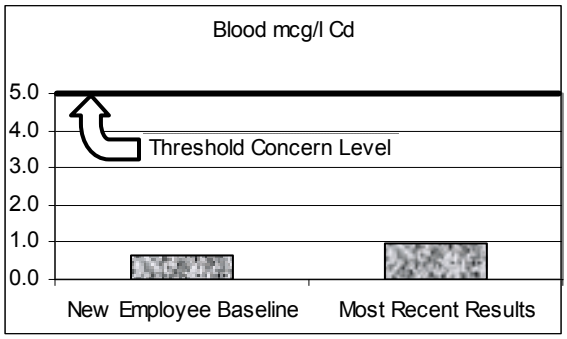

Fig 2. Baseline Vs current employee blood cadmium levels.

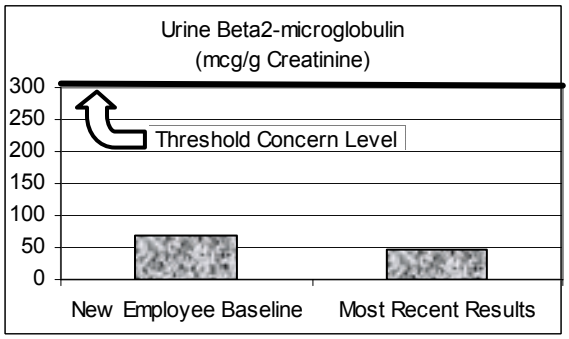

Fig 3. Baseline Vs current employee β-2 microglobulin levels (normalized to μg/g creatinine).

The next charts compare two employee sub-populations, smokers and non-smokers, for baseline (time of hire) blood and urine cadmium levels.

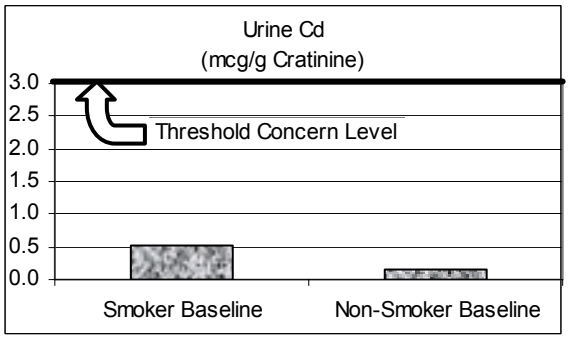

Fig 4. Smoker Vs non-smoker baseline urine cadmium levels (normalized to μgCd/g creatinine).

MEDICAL MONITORING ANALYSIS AND DISCUSSION

First, some background information is necessary. Urine cadmium levels are primarily indicative of long term cadmium exposure but are somewhat indicative of recent exposure, blood cadmium levels are primarily indicative of recent exposure, and β-2 microglobulin levels are a

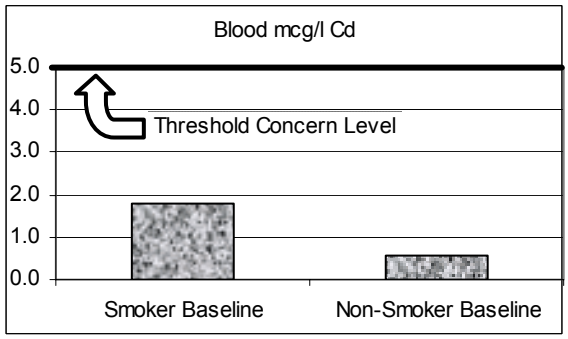

Fig 5. Smoker Vs non-smoker baseline blood cadmium levels.

secondary indicator of cadmium exposure[2]. Excretion of low molecular weight proteins such as β-2 microglobulin is an indicator of poor kidney health[3]. Medical monitoring results in the normal range are <3μg Cd per gram normalized to creatinine for urine, <5μg Cd per liter blood, and <300μg/g β-2 microglobulin normalized to creatinine[4].

The medical monitoring data presented show no significant change in any biological marker used for medical surveillance between time of hire and the most recent results for those employees working most intimately and for the longest times on CdTe module manufacturing processes. Calculated averages for urine show no difference for the time period studied. Blood cadmium levels show a nominal increase and β-2 microglobulin results show a nominal decrease.

Statistically meaningful differences are not possible to calculate due to a large total error in the test, the prevalence of a large number of results at the method detection limits and the relatively small number of data points at each time endpoint. According to Dr. Linda Aston, Pacific Toxicology Laboratory's Director of Occupational Services, the total error for these tests (considering precision and accuracy) approaches +/-20%. Larger sample populations than the 44 data points in this analysis would be necessary to distinguish statistically valid differences. Second, there is a prevalence of "detection limit" values in the results. For urine Cd levels, 27 of the 44 data points are below the method detection limit of 0.5μg Cd per gram creatinine and 16 of 44 data points for blood Cd levels were below the method detection limit of 0.5μg Cd per liter.

Even in the case of figures 4 and 5, which show that the average baseline (time of hire) blood and urine cadmium levels is apparently higher for smokers compared to non-smokers, attempted statistical tests failed. The T-test comparing the 14 non-smokers in this sub-population to the 15 non-smokers yielded a statistically significant difference in means at an error probability of < 2% for both urine and blood analyses. The F-test failed, however, indicating non-random sample variances even though no detection limit values were used in these calculations.

Clearly, all of the charted medical monitoring averages are well below the published concern thresholds and are typical of non-occupationally related exposure to cadmium background exposure from food, air and smoking habits. There is no individual employee in the First Solar medical monitoring database that has ever shown occupationally related urine or blood cadmium results above the published concern levels. Statistically significant differences in baseline Vs current cadmium levels and smokers Vs non-smokers are inconclusive probably because so many of the results are below the analytical detection limits for cadmium and there are not enough data points overall in the directly comparable sub-populations.

INDUSTRIAL HYGIENE RESULTS

The following table shows a range of industrial hygiene air sampling data for each major process step in the First Solar manufacturing process. Results are stated first for air samples obtained during the normal operating mode for each process then secondly for maintenance activities.

Employee Cadmium Exposure in $\mu g/M^3$	
Manufacturing Process	**Result**
Semiconductor deposition	<0.1 to 0.4
Sunny-side film removal	<0.1
Wet film treatments	<0.1 to 2.2
Cell interconnection	<0.1
Finalization	<0.1 to 2.4
Module recycling	<0.1 to 1.2
Results stated as "less than" (<) are below the stated analysis detection limit. All results are normalized to an 8-hour time weighted average. OSHA PEL = $5.0\mu g/M^3$	

Table 1. Cadmium air sampling data summary.

INDUSTRIAL HYGIENE DISCUSSION

Table 1 summarizes, and states in ranges, the results of hundreds of repetitive industrial hygiene air monitoring samples taken oven the years on the pilot CdTe module manufacturing processes. At a glance, it can be seen that these results compliment and support the low medical surveillance testing results described above. There are no module processing steps that result in worker exposure at or above $5\mu g/M^3$ for an 8-hour time weighted average which is the OSHA (US Occupational and Health Administration) PEL (permissible exposure limit) for cadmium[5].

These excellent results have been achieved by installing state-of-the-art engineering controls; primarily industrial ventilation equipment for capturing cadmium dust right at the point of generation. This equipment is specified, designed, sized and installed by professional ventilation engineers in conjunction with in-house environmental, health and safety staff. It is important to note that, despite the widespread and effective use of ventilation engineering controls in the First Solar module manufacturing process, it is not a "dirty" process. The OSHA PEL of $5\mu g/M^3$ is simply so low that these controls are required to meet this stringent regulatory requirement. For perspective, the permissible exposure limit for lead in the US is $50\mu g/M^3$; arsenic is $10\mu g/M^3$[6].

The only manufacturing activity that we have recorded in excess of the OSHA PEL is maintenance to the semiconductor deposition equipment. The First Solar high-speed vapor transport deposition process has a high semiconductor utilization rate but it is currently not possible to direct 100% of the inputted material to the glass substrate. With time, parts of the deposition chamber accumulate a small amount of CdS and CdTe semiconductors and must be cleaned. Additionally, worn out components must be repaired or replaced. Since local ventilation control is not practical for the large open area of the deposition chamber, workers wear appropriate respiratory protection such as powered air purifying respirators (PAPR's) equipped with High Efficiency Particulate Absolute (HEPA) filter cartridges to protect themselves from cadmium dust during these maintenance activities.

ENVIRONMENTAL RELEASE RESULTS

The table below shows a summary of cadmium releases to the environment.

Cadmium Environmental Release Data	
Land	First Solar is a small quantity hazardous (solid) waste generator (<1,000 Kg/month as defined by the USEPA) resulting mainly from disposal of cadmium contaminated personal protection devices and maintenance of process filtration equipment. Non-recoverable or recyclable cadmium contaminated equipment is incinerated when possible rather than landfilled to reduce ultimate Cd (ash) disposal volumes.
Air	First Solar emits no significant Cd to the atmosphere (<1μg/module produced) and meets the State of Ohio *de minimus* air emissions limits for cadmium.
Water	First Solar meets the local discharge limit of <0.3mg/l Cd to the City of Toledo treatment works.

Table 2. Cadmium environmental release data.

ENVIRONMENTAL RELEASE DISCUSSION

The cadmium compounds used in the First Solar manufacturing process originate as solid materials and exit the process as solid materials even though they may be used in all forms (vapors, solutions and solids) during the process. Cadmium contaminated wastewater solutions are precipitated and pressed to a high solids content. Cadmium vapors condense on the cool spots in the vacuum deposition furnace. Filter elements accumulate fine cadmium dust particles from the laser ablation cell isolation step as well as from other processes. Ultimately, cadmium contaminated manufacturing wastes must be disposed of as a solid

waste. However, since the product is a thin-film, only a few microns thick, the amount of cadmium wasted per unit produced is very small. It is not anticipated that any individual First Solar manufacturing facility would ever become more than a small quantity hazardous waste generator regardless of production throughput. Also, of the waste disposed, only a small fraction is actually cadmium. More than 90% of the total weight disposed is contaminated, but not recoverable, inert material. Further, contaminated solid materials are segregated for combustibility. All combustible wastes are incinerated to reduce the ultimate disposal volumes (as ash) in the hazardous waste landfill. First solar always endeavors to reduce wastes where possible and practical.

There are no significant cadmium environmental emissions to air or water and no other regulated emissions such as VOC's (Volatile Organic Compounds).

SAFETY RESULTS

Injury/Illness Case Rate Comparison for 1999		
Industry	**Total Cases**	**Lost Workday Cases**
All Manufacturing	9.7	2.3
Electronic Equip.	5.9	1.3
First Solar Pilot	3.8	1.2

Table 3. Safety statistics.

SAFETY DISCUSSION

The safety performance results for our pilot manufacturing facility have been excellent. Table 3 shows that total case rates and cases involving lost workdays are lower for the First Solar pilot operation than for general industry and the electronic equipment manufacturing sector[7]. These results are achieved with the same attention to detail as all of the hazardous materials management issues previously discussed. Individual compliance programs on many topics including laser safety, forktrucks, cadmium compliance, hazard communication, respirators, lockout-tagout, electrical safety, and many others are maintained and employees are routinely trained on them.

More importantly, activities beyond regulatory compliance have been the real pay-off for the First Solar safety process. For example, a hazard recognition program using a simple numerical system to gage potential accident risk and probability is used to effectively find hazards and prevent accidents from ever occurring. Finally, a cross-functional and cross-level safety council meets regularly to manage responses to significant hazards, incidents and accidents.

SUMMARY

Medical monitoring data, supported by industrial hygiene air sampling data, shows no significant occupationally related cadmium exposure to workers in the First Solar manufacturing process.

The OSHA Cadmium Standard, 29CFR§1910.1027, mandates, among other requirements, medical monitoring of employees when they are exposed at or above the OSHA 8-hour time weighted average permissible exposure limit for cadmium of 5µg/M^3 for 30 days or more per year. Industrial hygiene measurements of the First Solar CdTe PV module pilot-manufacturing environment show no areas or routine activities where employees are exposed at these levels or frequencies. Nonetheless, the effort and expense of managing cadmium exposure hazards *as if* this regulation was relevant to our operations has been worthwhile. We have the data and experience to anticipate, recognize and prevent cadmium related health threats to our workforce. Activities such as smoking may be more significant to an individual's cadmium exposure and uptake than exposure on the job.

Likewise, the CdTe PV module manufacturing is easy on the environment. Practically no air or water cadmium emissions are generated with First Solar manufacturing process. Small amounts of solid waste, mainly resulting from maintenance of control equipment such as HEPA air filters and wastewater treatment are generated and disposed of in accordance with the best available treatment technologies.

Last, the diverse and involved staff participating in the First Solar Safety Council, using a formal hazard recognition process to pro-actively identify and prevent equipment, property and human health losses, has achieved an excellent safety performance record.

ACKNOWLEDGMENT

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